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Research Council

# A COMPARISON OF EVAPORATION ESTIMATES FROM THE CLIMATOLOGICAL REFERENCE STATION OF THE SASKATCHEWAN RESEARCH COUNCIL

by

Fei Qingpei

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S.R. Shewchuk

SRC Technical Report No. 190

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The Saskatchewan Research Council has operated this Climatological Reference Station (CRS) on the University of Saskatchewan grounds for nearly 25 years. A special acknowledgement is due to the Atmospheric Environment Service whose partial support for this facility has allowed us to maintain a keen interest within our organization in the field of climatology.

The long and stable record of observation at the CRS is the result of high quality work and dedication from many observers at this site over the years. We would like to sincerely thank them all. Perhaps the longest and most excellent period of record was maintained by Mr. Joe Calvert. Mr. Ray Begrand, who is currently in charge of our CRS, provided significant assistance in assembling the data for this report.

## LIST OF SYMBOLS

$X_1$ Class A pan or its evaporation.

$X_2$ Bellani or its evaporation.

$X_3$ White atmometer or its evaporation.

$X_4$ Black atmometer or its evaporation.

$U_2$ Wind mileage measured at 2-metre level; in km/day.

$T_s$, $T_u$ $T_d$ Temperature of water surface, air and dew point; in $^oC$.

$e_s$, $e_a$, $e_d$ Saturation vapour pressure at above temperatures; in mb.

$R_c$ Global radiation; in $MJ/m^2/day$.

r Radiation reflection coefficient.

n/N Ratio of actual/possible hours of sunshine.

H Net radiant energy available at surface

$\beta$ Bowen's ratio

$\gamma$ Psychrometric constant, 0.66 mb/$^oC$ at sea level.

$\Delta$ Slope of the saturation vapour pressure curve; in mb/$^oC$.

$E_o$ Evaporation rate of aerodynamic term from open water (Class A pan) in mm/day.

$E_a$ Value of $E_o$ obtained by putting $e_s = e_a$ in mm/day.

$E_e$ Evaporation rate of energy term; in mm/day.

$E_p$ Potential evapotranspiration in mm/day.

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## SUMMARY

Four evaporimeters have measured the water vapour flux at the Climatological Reference Station of the Saskatchewan Research Council for the past eleven years. It is the purpose of this report to appraise the performance and usefulness of these instruments in the measurement of evaporation. The White and Black spherical atmometers give data that is consistent with the Class "A" pan. The Bellani plate produces data that consistently does not correlate well with the other evaporimeters. The evaporimeters correlate well with each other during the month of June. The Class "A" pan was considered the best estimator of evaporation.

# 1. A COMPARISON OF THE CLASS "A" PAN AND OTHER ATMOMETER ASSEMBLIES

## 1.1 Introduction

The Saskatchewan Research Council (SRC) has operated a Climatological Reference Station (CRS) on the University of Saskatchewan grounds for nearly 25 years. A recent report describing the observation at the CRS is given by Wheaton et al 1986. One series of measurements that have been conducted for more than 11 years is a comparison of evaporation measurements from four differing evaporimeters. It will be the purpose of this report to study the comparative results from these instruments during this period and to study evapotranspiration measurements from this data.

This report is divided into two sections. The first section deals with a comparison of the measurements of evaporation from the evaporimeters. The second part deals with the estimation of evapotranspiration by the Penman approach.

In this report we shall consider the units of evaporation to be kg/m2/day. The evaporation was thus considered as a flux of water vapour. It was felt that this was a more logical way to describe the evaporation phenomenon. It is more physically correct when considering an intercomparison of instruments.

Evaporation is measured with an evaporimeter. Besides the Class "A" pan, several different kinds of atmometers have been employed in Canada. A black Bellani plate which consists of a glass tube with Livingston-Thone wool mercury valve has been in general use since 1920. Later on, all atmometers were improved. The U tube valve was introduced by Shive (1930) and with modification was used by Wilson (1930). Studying evaporating data from the Piche evaporimeter, Prescott and

Sterk (1951) indicated that the data could not be regarded simply as an index for evaporation from open water surfaces, soil or vegetation.

In the latter half of the 1950's Robertson began experimenting with an atmometer of his own design to try to overcome frost susceptibility and some other problems associated with the use of the Bellani plate (1961). Six different atmometer assemblies were put to use in Canada Department of Agriculture, Experimental Farm, Beaverlodge, Alberta. Using data obtained at Beaverlodge, Alberta, Carder (1960) found that the daily evaporation from the Bellani plate was highly correlated with that from the black porous disc, which was based on the principle of the Piche atmometer. Mukammal (1961) gave a series of comparisons between observed evaporation from the Class "A" pan, the black Bellani plate and the Piche atmometer and computed evaporation by mass transfer and energy budget methods. He agreed with Prescott and Sterk's point about the Piche atmometer. He also suggested that the Bellani is very responsive to wind but less so to net radiation, implying different conversion factors are required for different ranges of evaporation and different locations, and that the Class "A" pan observation be converted into a reasonably reliable estimate of lake evaporation.

For the sake of minimizing occurrence of water loss by wind action during periods of strong gusty winds, the black porous double-disc was in routine use. Williams (1967) compared the black porous double-disc with the Bellani plate, and suggested that the daily latent evaporation data from the double-disc exceeded those from the plate, while the high correlation coefficient between the double-disc and the plate was similar to that found between the black porous disc and the Bellani

plate in Carder's study. Williams further indicated that two double-disc atmometers were highly correlated and they did not differ significantly, but the differences between two Bellani plates were significant. Evaporation data obtained from pans of different sizes and colours were studied (Brutsaert and Shaw, 1968).

Furthermore, in some cases a close agreement was found between evaporation computed by formulae based on aerodynamics and energy balance methods or measured directly by lysimeter observed from atmometers. This has greatly encouraged the continued use of small evaporimeters, and has led to a search for coefficients or empirical formulae for deriving actual evaporation rates at any time and place from evaporimeters, and for a statistical relationship between evaporation from these units and from meteorological parameters.

Evapotranspiration estimates from atmometers and pans were studied by Pelton and Korven (1969) at Swift Current, Saskatchewan. They realized that some evaporimeters could be used to predict evapotranspiration by alfalfa to an accuracy of about 1.5 mm/day on a daily basis. Thom, Thony and Vaudin (1981) investigated the feasibility of estimating potential transpiration from the data of evaporimeters, using continuous micrometeorological measurements on certain days from hour to hour. The measurements were of particular help in interpreting physical behaviour.

Evapotranspiration data can be utilized in various agricultural engineering applications including the design of irrigation and drainage systems, water conservation structures and the scheduling of tillage operations, especially in estimating irrigation requirements and evaluating agroclimatic resources. On most occasions, latent evaporation,

which can be considered as an index of the drying ability of the air, is used for deriving actual evapotranspiration.

Latent evaporation is measured with an evaporimeter. Besides the Class "A" pan, different kinds of atmometers have been employed in Canada. A number of comparisons of evaporation among Class "A" pan and atmometers have been done since the 1950's. Many useful results have been obtained. But there are still some uncertainties remaining.

## 1.2 Materials and Methods

There are four evaporimeters in routine use at the Climatological Reference Station of Saskatchewan Research Council (SRC). They are the Class "A" pan, black Bellani plate atmometer, white sphere atmometer and black sphere atmometer.

The Class "A" pan is widely used all over the world for measuring water loss. The pan employed at the SRC is 120 cm in diameter, 25 cm depth of edge with 19 cm depth of water, and is exposed above the ground on a wooden frame support. The pan itself is made of steel.

The Bellani plate consists of a flat circular evaporating surface of black porous porcelain covering the top of a glazed porcelain funnel. Water is conducted to the funnel (from a glass tube which acts as a reservoir and measuring device). The area of the evaporating surfaces is shown in Table 1.

The white sphere is made of white porous porcelain. It has a spherical evaporating surface which is supported by a glazed porcelain stem. The stem is connected via a "U" feeder tube to a vertical cylindrical 250 cc graduated glass reservoir. The water which evaporated

Table 1. Structure of the Class "A" Pan and the Atmometers

| | Elevations | Features of Evaporating Surfaces | Diameters | Areas | Diameter of Stems | Cross Area of Stems | Actual Areas of Evaporation |
|---|---|---|---|---|---|---|---|
| Class "A" Pan | 40 cm height of edge | flat round surface | 120 cm | 1.131 $m^2$ | | | 1.131 $m^2$ |
| Bellani | 160 cm | plate | 6.80 cm | 0.003632 $m^2$ | | | 0.003632 $m^2$ |
| White | 160 cm | sphere | 5.38 cm | 0.009093 $m^2$ | 2.54 cm | 0.000507 $m^2$ | 0.008586 $m^2$ |
| Black | 160 cm | sphere | 5.38 cm | 0.009093 $m^2$ | 2.54 cm | 0.000507 $m^2$ | 0.008586 $m^2$ |

from the sphere of the white sphere is replaced by distilled water which is fed from the reservoir.

The black sphere has the same structure as that of the white sphere. The difference is only that the evaporating surface of the black sphere is made of black porous porcelain.

All assemblies were mounted at the observing site of the SRC so that the ambient conditions are considered to be the same. The evaporating surface of the three atmometers is 160 cm above the ground. The Class "A" pan is 40 cm height of edge above the ground.

The daily evaporation from four evaporimeters was compared during the summers of 1975 to 1985. The observation of evaporation lasted 11 years. Statistical analyses were performed on the latent evaporation data for the days from June to September, so there were more than 1000 evaporating samples available for each assembly. For the purpose of comparison, water loss from the four evaporimeters was converted into water flux ($Kgm^{-2}D^{-1}$).

## 1.3 Comparison of Yearly Means

For simplification, the water flux from the Class "A" pan was expressed as $X_1$. $X_1$ was the mean water flux, $Sx_1$ standard deviation and $N_X$, the number of samples. Others were $X_2$, $X_3$ and $X_4$ respectively (Table 2). From Table 2, it could be seen that the Class "A" pan had the smallest water flux. The water flux from the Bellani plate reached 17.89 $Kgm^{-2}D^{-1}$, and appeared to be as as much as 2.8 times that from the Class "A" pan. It was not surprising that the water flux from the black sphere was more than from the white sphere because the black sphere

Table 2. Yearly Mean and Standard Deviation of Water Fluxes ($Kgm^{-2}D^{-1}$)

| YEAR | Class "A" Pan ($X_1$) | | | Bellani ($X_2$) | | | White ($X_3$) | | | Black ($X_4$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $X_1$ | $Sx_1$ | $Nx_1$ | $X_2$ | $Sx_2$ | $Nx_2$ | $X_3$ | $Sx_3$ | $Nx_3$ | $X_4$ | $Sx_4$ | $Nx_4$ |
| 1975 | 5.97 | 2.51 | 111 | 11.78 | 5.37 | 111 | 5.68 | 2.76 | 111 | 7.55 | 3.34 | 111 |
| 1976 | 6.84 | 2.92 | 113 | 19.23 | 8.83 | 113 | 7.29 | 3.61 | 113 | 9.01 | 3.89 | 113 |
| 1977 | 5.71 | 2.81 | 121 | 19.52 | 9.53 | 121 | 5.82 | 2.99 | 121 | 7.56 | 3.72 | 121 |
| 1978 | 6.42 | 3.09 | 122 | 26.27 | 11.38 | 122 | 7.14 | 3.34 | 122 | 8.48 | 3.82 | 122 |
| 1979 | 6.48 | 2.40 | 117 | 16.17 | 6.27 | 117 | -- | -- | 0 | 8.95 | 3.11 | 117 |
| 1980 | 6.20 | 2.82 | 101 | 13.39 | 6.93 | 101 | 6.24 | 3.13 | 101 | 8.58 | 3.99 | 101 |
| 1981 | 6.80 | 3.13 | 122 | 11.53 | 6.38 | 122 | 7.82 | 4.03 | 122 | 9.59 | 4.53 | 122 |
| 1982 | 5.85 | 2.62 | 103 | 12.52 | 5.26 | 103 | 5.93 | 2.59 | 103 | 7.75 | 3.24 | 103 |
| 1983 | 6.83 | 2.79 | 100 | 21.95 | 8.89 | 100 | 7.28 | 3.16 | 100 | 9.04 | 3.64 | 100 |
| 1984 | 8.02 | 3.80 | 113 | 31.17 | 14.03 | 113 | 8.32 | 4.26 | 113 | 10.44 | 4.81 | 113 |
| 1985 | 6.01 | 2.79 | 108 | 12.21 | 5.50 | 108 | 6.20 | 2.79 | 108 | 7.99 | 3.24 | 108 |
| TOTAL | 6.47 | 2.96 | 1231 | 17.89 | 10.57 | 1231 | 6.79 | 3.43 | 1114 | 8.64 | 3.88 | 1231 |

could absorb more solar energy in the day time than the white.

T-Testing indicated that the difference of means in each pair exceeded the level of significance except that of $X_1$ and $X_3$. The value of t from $X_1$ and $X_3$ was 2.33, which just reached the 5% level of significance ($t_{0.01}$=2.33). That is to say, the water flux of the Class "A" pan is similar to that of the white sphere.

Figure 1 indicated the curves of yearly change in water flux. The Class "A" pan, the white sphere and the black sphere had the same pattern of change. The curve of the white sphere was quite close to that of the pan, but the pattern fitted with that of the black. The curve of the Bellani behaved oddly. The biggest numerical value was almost three times bigger than the smallest one. Some years it changed in the opposite direction to the other curves. It is difficult to explain why the pattern of the Bellani plate was different from others. The possible reason could be that different Bellani plates, especially ones having different indices of evaporation surface, had been used.

The F-testing of variance analysis showed that the difference of yearly means from each evaporimeter was significant. It appears that the white sphere was a little more responsive than the black sphere and the Class "A" pan. The Class "A" pan was less responsive than others because of the large amount of water.

## 1.4 Comparison of Monthly Means

The evaporation from the Class "A" pan and the white sphere was similar in July (Table 3). But the difference increased in August and September. In fall, the evaporation from the Class "A" pan reduced more quickly than from the white sphere. Inversely, the evaporation from

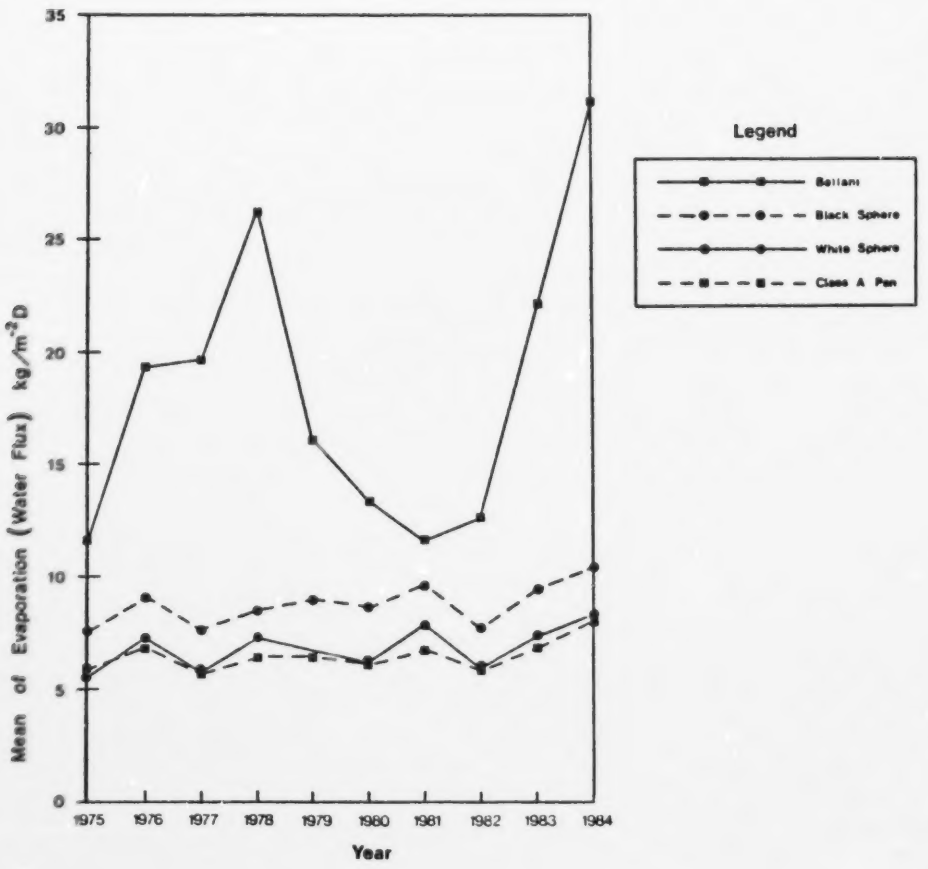



Figure 1. Curves of yearly water flux from CRS.

the white sphere in June was 4.3% less than that from the Class "A" pan (Table 4). The data of Table 4 showed that there were differences in relative water flux. In September, the rate was greatest, while the July rate was the least.

## 1.5 Correlation Coefficient between Daily Water Fluxes

Regression analyses to compare evaporimeters in pairs were performed on the water flux data for the days of each year from June to September and for total samples from 1975 to 1985. The data of Table 5 show the correlation coefficients from all pairs. In Table 5, the arbitrary two sets of data were correlated, although the differences between two means were significant as indicated in Table 2.

The two sets of data from $X_3$ and $X_4$ were closely correlated as indicated by the high correlation coefficient and the goodness of fit to a straight line of the plotted data (Figure 2). It is obvious that because of the same shape and texture, the white sphere and the black sphere resemble each other in the effect of evaporation. In Figure 2, most points gathered closely along the line, so that some points far apart from the line must be considered as possible observing errors.

The correlation coefficient between $X_2$ and $X_3$ (and $X_4$) were high except in 1981, but that from total samples dropped sharply. This situation was caused by the evaporation of the Bellani plate. Some years the water loss of the Bellani plate was more than that of the white sphere, even more than of the black sphere. Other years it was much less than that of the other two atmometers. Even if the data of 1981 were deleted, the correlation coefficient from total samples was still low. So, the Bellani plate atmometer showed unstable features

Table 3. Mean of Monthly Water Flux ($Kgm^{-2}D^{-1}$)

| | June | July | August | September |
|---|---|---|---|---|
| Class "A" Pan | 7.0 | 7.6 | 6.6 | 4.5 |
| Bellani | 19.1 | 20.4 | 19.3 | 13.8 |
| White | 6.7 | 7.6 | 7.3 | 5.6 |
| Black | 8.9 | 9.5 | 9.3 | 6.8 |

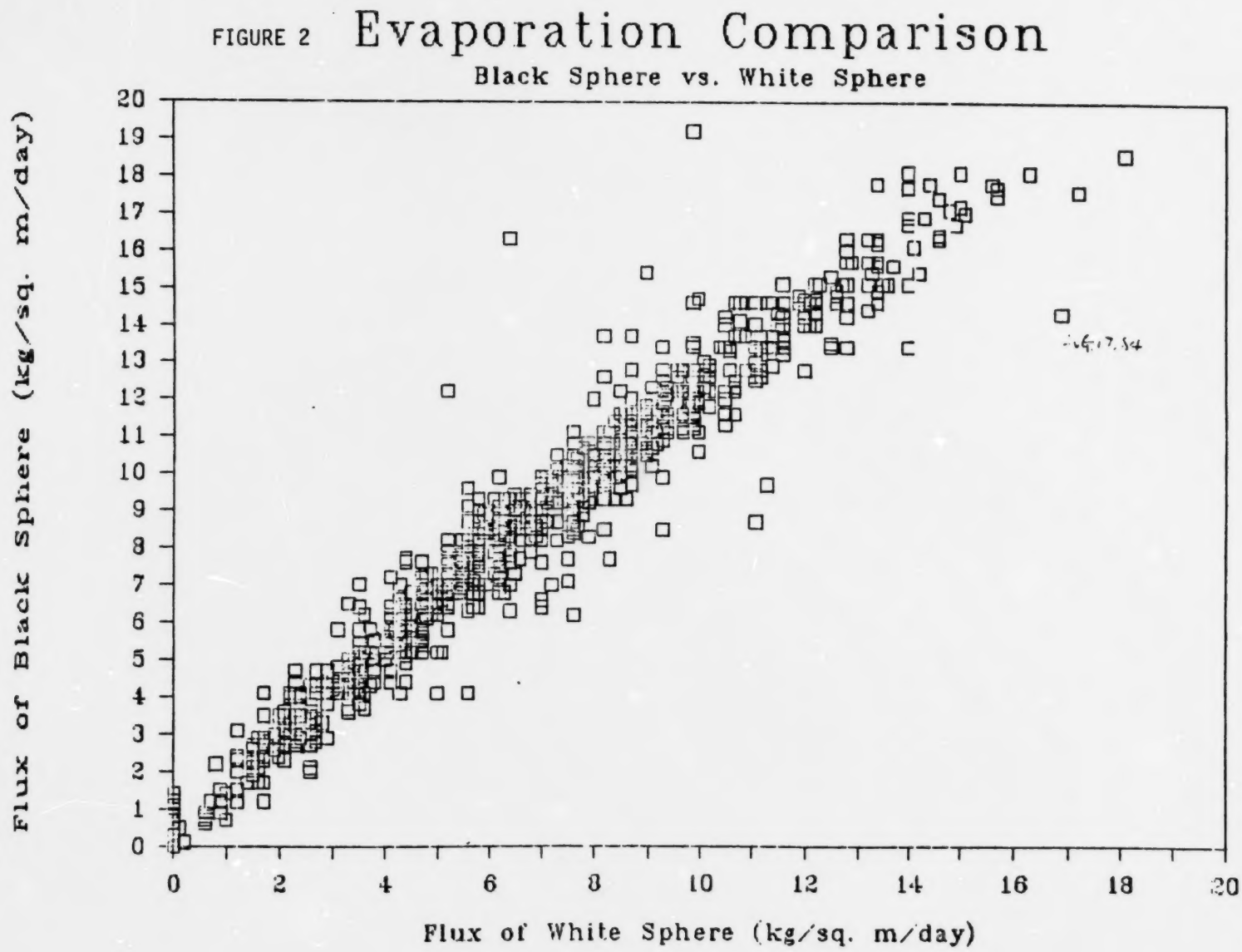
Table 4. Relative Water Flux from Various Evaporimeters in Different Months

| | June | July | August | September |
|---|---|---|---|---|
| Class "A" Pan | 100% | 100% | 100% | 100% |
| Bellani | 272.9 | 268.4 | 292.4 | 306.7 |
| White | 95.7 | 100.0 | 110.6 | 124.4 |
| Black | 127.1 | 125.0 | 140.9 | 151.1 |

Table 5. Correlation Coefficients Between Daily Water Flux from Different Evaporimeters

| YEAR | Evaporimeters Correlated | | | | | |
|---|---|---|---|---|---|---|
| | $X_1$ $X_2$ | $X_1$ $X_3$ | $X_1$ $X_4$ | $X_2$ $X_3$ | $X_2$ $X_4$ | $X_3$ $X_4$ |
| 1975 | 0.86 | 0.82 | 0.84 | 0.98 | 0.98 | 0.99 |
| 1976 | 0.77 | 0.77 | 0.78 | 0.99 | 0.99 | 0.99 |
| 1977 | 0.92 | 0.92 | 0.93 | 0.99 | 0.99 | 0.98 |
| 1978 | 0.88 | 0.86 | 0.87 | 0.98 | 0.99 | 0.98 |
| 1979 | 0.84 | -- | 0.81 | -- | 0.95 | -- |
| 1980 | 0.91 | 0.86 | 0.90 | 0.96 | 0.98 | 0.96 |
| 1981 | 0.77 | 0.84 | 0.87 | 0.66 | 0.74 | 0.98 |
| 1982 | 0.74 | 0.74 | 0.71 | 0.97 | 0.91 | 0.93 |
| 1983 | 0.87 | 0.84 | 0.84 | 0.98 | 0.97 | 0.97 |
| 1984 | 0.79 | 0.83 | 0.85 | 0.95 | 0.99 | 0.98 |
| 1985 | 0.88 | 0.85 | 0.87 | 0.98 | 0.97 | 0.97 |
| TOTAL(R) | 0.708 | 0.831 | 0.846 | 0.785 | 0.798 | 0.970 |
| Number of Samples | 1231 | 1114 | 1231 | 1114 | 1231 | 1114 |

FIGURE 2


Evaporation Comparison
Black Sphere vs. White Sphere
Flux of Black Sphere (kg/sq. m/day)
Flux of White Sphere (kg/sq. m/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
2
4
6
8
10
12
14
16
18
20

especially in long term operation.

The correlation coefficients between $X_1$ and $X_3$ (and $X_4$) were consistent, including that from the total samples. It suggested further that the white and the black should have a similar evaporating effect. It would be feasible to use a regression equation to calculate water flux of a white atmometer from a black atmometer, and vice versa. In this study, the regression equation is $X_3$=-0.396+0.840 $X_4$ for total measurements. For simplification, the water flux of the black sphere could be estimated directly from that of the white sphere multiplied by 1.27, which was the coefficient for calibrating. The error was less than 5% on the average. Figures 3, 4 and 5 compare the regression lines for the Class "A" pan with the Bellani plate, white sphere and black sphere respectively.

The correlation coefficients between the Class "A" pan and the Bellani plate were lower than that between it and the other atmometers. It was apparent that they were influenced by different microclimate conditions. The Bellani plate is very responsive to wind, but less so to net radiation. The lowest correlation appeared between the Class "A" pan and the Bellani plate. The results suggest that the Bellani plate observations are less consistently related to the evaporation of Class "A" pan, and that different conversion factors may be required for different ranges of evaporation amounts, as well as for different calibrating factors.

FIGURE 3

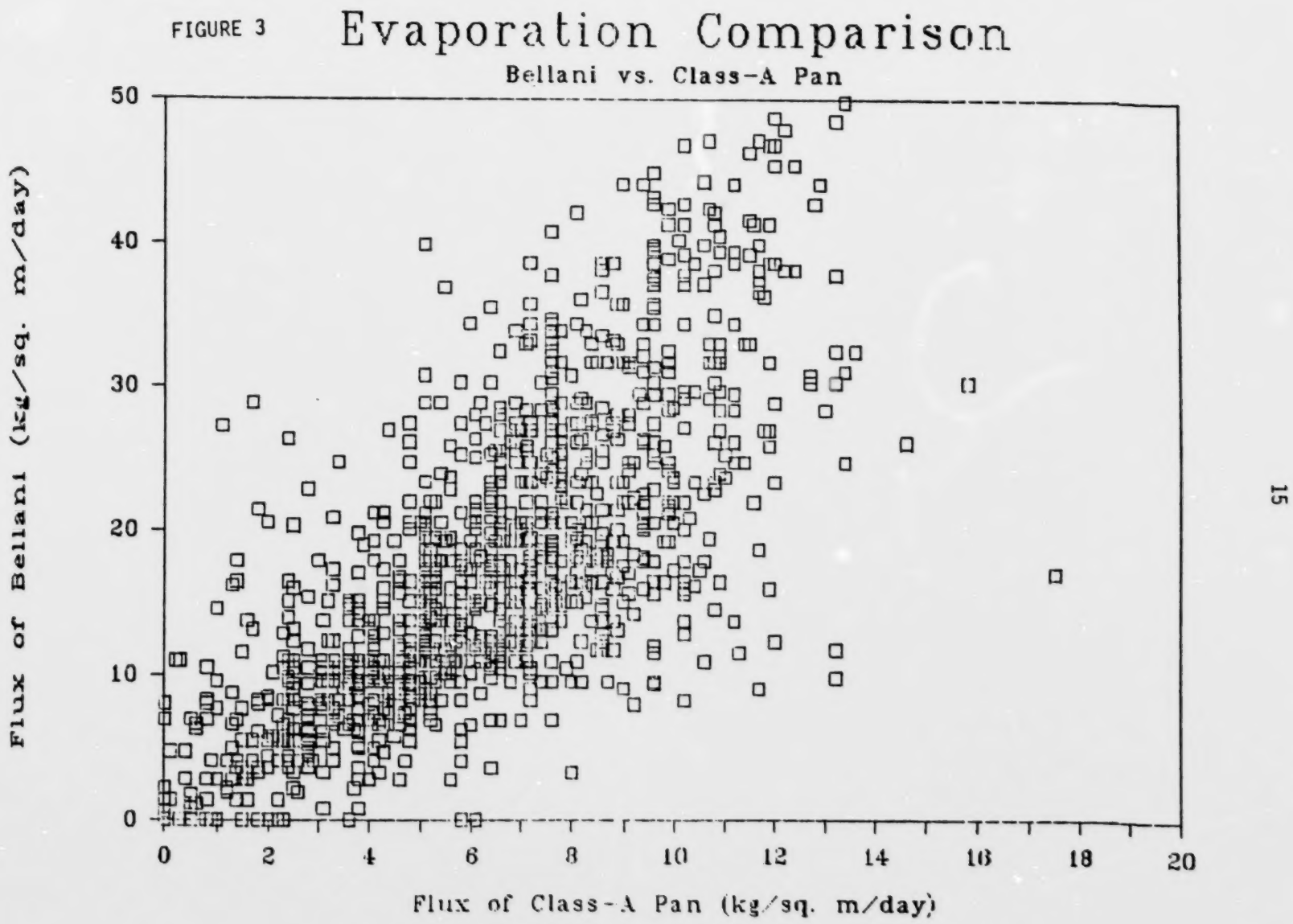

Evaporation Comparison
Bellani vs. Class-A Pan
Flux of Bellani (kg/sq. m/day)
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
Flux of Class-A Pan (kg/sq. m/day)

FIGURE 4

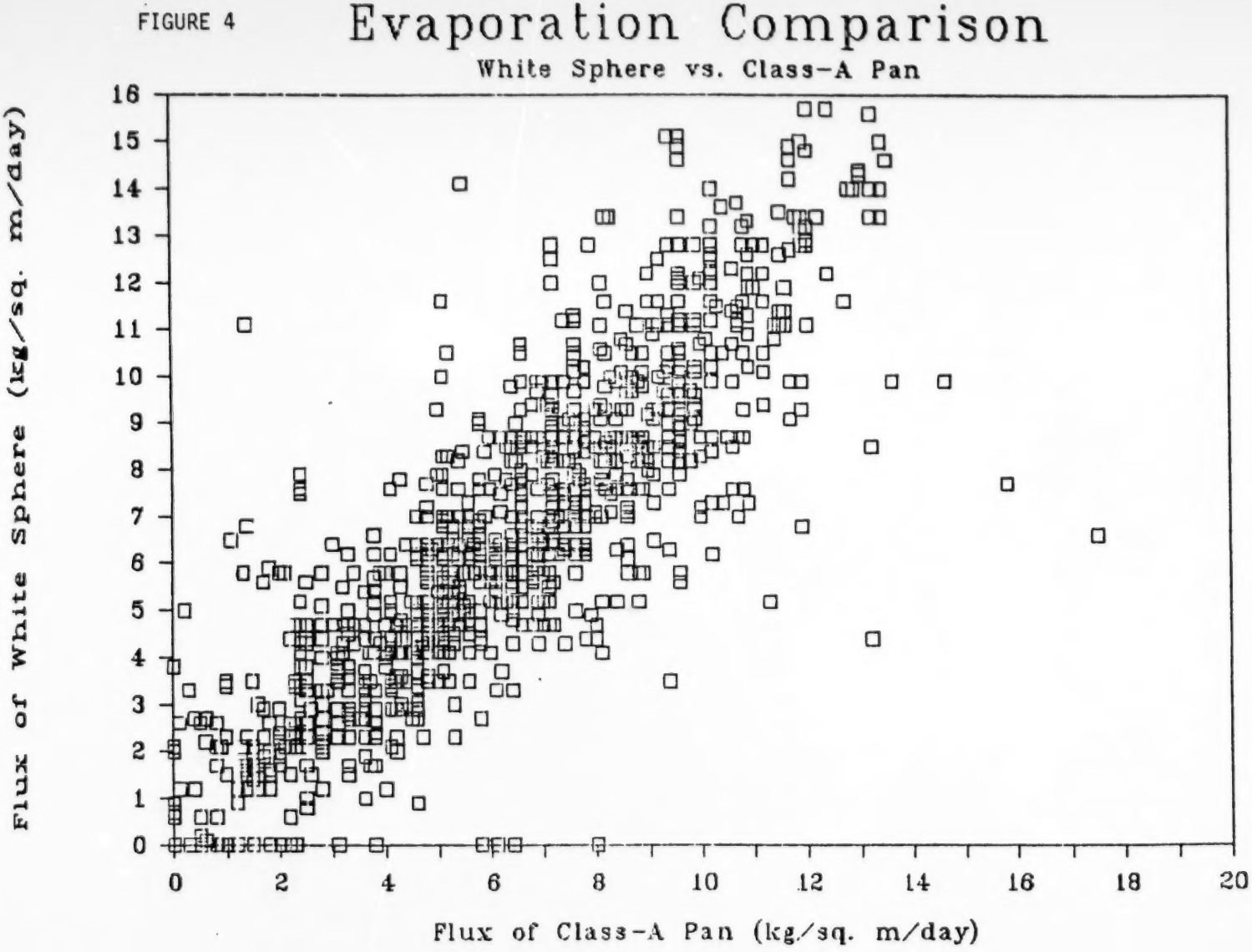
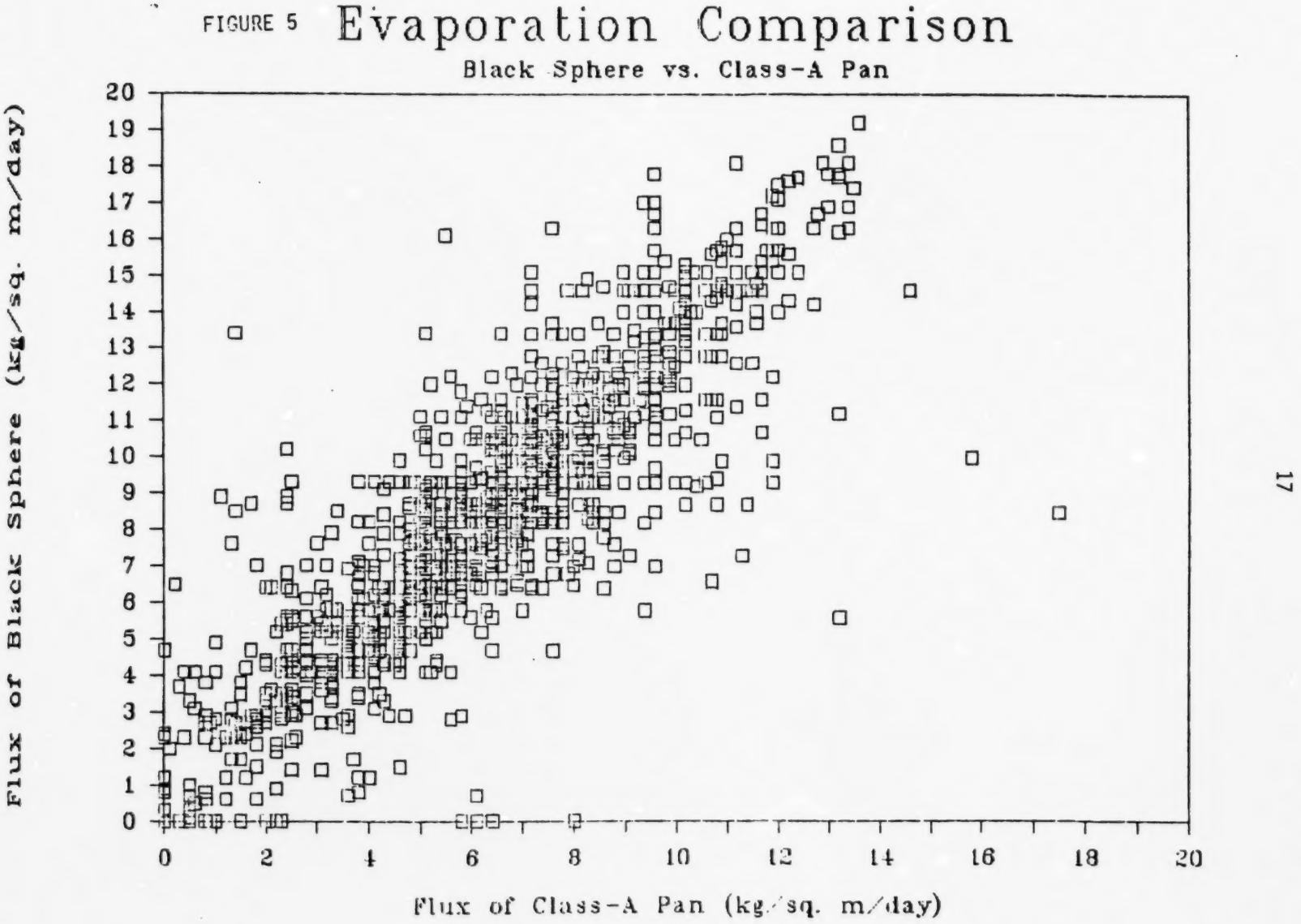

Evaporation Comparison
White Sphere vs. Class-A Pan
Flux of White Sphere (kg/sq. m/day)
Flux of Class-A Pan (kg/sq. m/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
0
2
4
6
8
10
12
14
16
18
20

FIGURE 5


Evaporation Comparison
Black Sphere vs. Class-A Pan
Flux of Black Sphere (kg/sq. m/day)
Flux of Class-A Pan (kg/sq. m/day)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
2
4
6
8
10
12
14
16
18
20

# 2. EVAPOTRANSPIRATION ESTIMATES FROM CLASS "A" PAN AND ATMOMETERS

## 2.1 Introduction

The Class "A" pan and atmometers have been widely used to estimate potential evapotranspiration from irrigated crops. They have also been used to estimate the areal evapotranspiration for assessing a long term water budget in water-balance studies. Atmometers which expose a moist, porous surface to the atmosphere are thought to respond quickly to environmental influences, whereas the Class "A" pan with broad free-water surface has a longer time constant.

This section of the report compares estimated evapotranspiration by these instrumental methods to each other. The applicability of each instrument is evaluated for the purpose of day-to-day evaporation and long period estimations.

## 2.2 Review of Penman's Equation

Potential evapotranspiration is normally estimated from a solution of the aerodynamic term and the energy balance term. For the Class "A" pan, the aerodynamic term, $E_o$, of Penman's formula was calculated from Eq.(2.1) given by Penman (1956), using values of saturation vapour pressure deficit, in mb, and wind mileage in $kmD^{-1}$.

$$E_o=0.263(e_s-e_d)(0.5+U_2/160.9) \qquad (2.1)$$

For the three atmometers, $E_a$, the value of $E_o$ obtained by putting $e_s=e_a$ was calculated from Eq.(2.2).

$$E_a=0.263\ (e_a-e_d)(0.5+U_2/160.9) \qquad (2.2)$$

The energy term of Penman's equation, $E_e$, with some simplification, is shown as follows:

$$E_e = H/(1+\beta) \tag{2.3}$$

$$H = R_c(1-r) - \alpha\, Ta^4(0.56-0.08\sqrt{e_d})(0.1+0.9n/N) \tag{2.4}$$

in which H is net radiant energy available at surface, and $\beta = \gamma(T_s-T_a)/(e_s-e_d)$ is Bowen's ratio.

As given by Penman (1948), the potential evapotranspiration $E_p$, is shown in Eq.(2.5):

$$E_p = (H\Delta+Ea\gamma)/(\Delta+\gamma) \tag{2.5}$$

where $E_a$ is calculated from Eq.(2.2); $\gamma$ = psychrometric constant $0.66 mb\,^{o}C^{-1}$ at sea level. At any altitude $\gamma = 0.66\ (P/P_s)$ should be taken, where P and $P_s$ are atmospheric pressure at sites and at sea level respectively. $\Delta$ = slope of the saturation vapour pressure curve in $mb\,^{o}C^{-1}$.

$$\Delta = \frac{dea}{dT_a} = \gamma'\beta' ea/(Ta+\beta') \tag{2.6}$$

in which $\gamma'$ and $\beta'$ are 17.27 and 237.3°C, respectively, when T 0°C or 21.88 and 265.5°C respectively, when T>0°C.

## 2.3 A Comparison of Evaporation from Evaporimeters and Calculated Evapotranspiration

A comparison was made among the atmometers, as well as among components of potential evapotranspiration. For simplification, $X_1$, $X_2$, $X_3$, $X_4$ represent Class "A" pan and its evaporation, Bellani plate, white atmometer and black atmometer and their evaporation respectively. In the calculation, the average weather elements of Y-day period were taken. Y is equal to 1, 3, 5, 7, 10, 15, 20, 25, and 30. The correlation coefficients between evaporation of the evaporimeters and calculated evapotranspiration are shown in Table 6. The number of

samples for each evaporimeter and in each Y-day period are listed at the bottom row of Table 6. Because the evaporation data of the white atmometer were missing for 1979, the total number of samples of the White is less than the others.

In some approaches to evapotranspiration, different weather conditions were considered, i.e. analyses were taken separately on days with rain and days without rain. It is difficult to say if there are tremendous differences between days with light rain and overcast days. For general use, it is appropriate to take all kinds of weather conditions into account when calculating evapotranspiration, except heavy rain days with probably water splashing out, in particular for the Class "A" pan.

(a) Aerodynamic term ($E_o$, $E_a$)

The correlation coefficients in Y-day period between $E_o$ and $X_1$ are listed in Table 6. It shows that correlation coefficients are more than 0.90 for periods greater than 3 days. If daily weather elements are used, the correlation coefficient is only 0.82, being the lowest value. For $E_o$ and $X_1$ in a 5-day period, the line of best fit is given in Eq.(2.7).

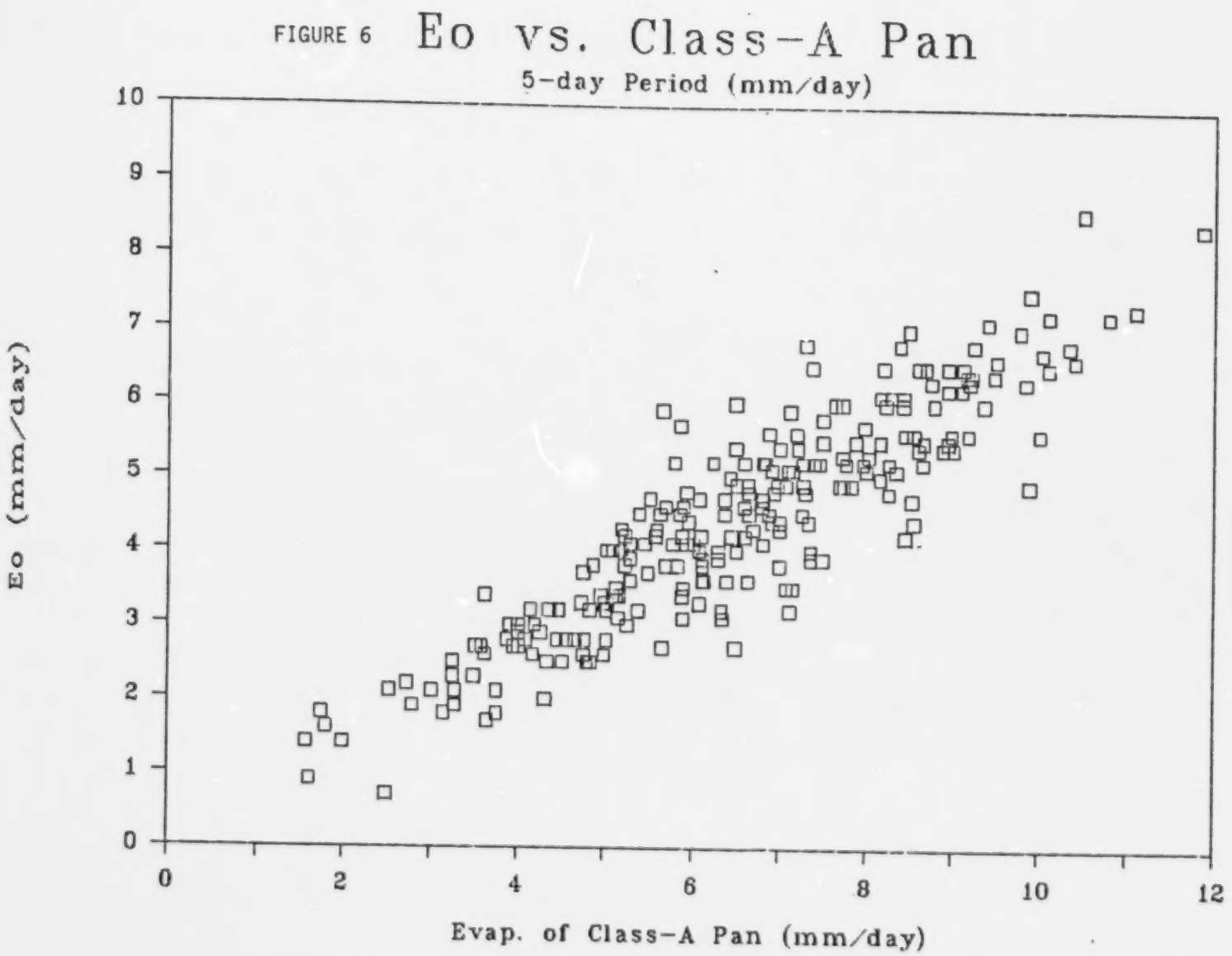
$$E_o = 0.663X_1 + 0.0993 \qquad (2.7)$$

The mean standard error of the estimate is 0.633 which is 15 percent of $E_o$; the regression accounts for 82 percent of the variance. Figure 6 shows the scattered points. The correlation coefficients do not make much difference if more than the 3-day period is taken. It is feasible to estimate average daily $E_o$ for the 5-day to the 30-day period. The longer the time frame the better the estimate of $E_o$.

Table 6. Correlation Coefficients between Evaporation as measured by the Evaporimeters and the Calculated Evaporation

| Y-day Period | | 1-day | 3-day | 5-day | 7-day | 10-day | 15-day | 20-day | 25-day | 30-day |
|---|---|---|---|---|---|---|---|---|---|---|
| $E_o$ | Class "A" Pan | .821 | .889 | .903 | .906 | .904 | .913 | .918 | .895 | .919 |
| $E_a$ | Bellani | .766 | .749 | .742 | .729 | .703 | .710 | .699 | .692 | .722 |
| | White | .910 | .933 | .949 | .945 | .952 | .950 | .965 | .964 | .965 |
| | Black | .890 | .921 | .941 | .940 | .946 | .939 | .956 | .954 | .957 |
| $E_e$ | Class "A" Pan | .592 | .655 | .656 | .671 | .681 | .729 | .722 | .591 | .702 |
| | Bellani | .401 | .349 | .322 | .294 | .277 | .279 | .239 | .144 | .183 |
| | White | .435 | .392 | .368 | .351 | .347 | .406 | .407 | .175 | .412 |
| | Black | .502 | .471 | .454 | .439 | .442 | .515 | .518 | .310 | .504 |
| $E_p$ | Class "A" Pan | .823 | .884 | .890 | .888 | .890 | .898 | .904 | .865 | .895 |
| | Bellani | .674 | .619 | .586 | .546 | .511 | .490 | .470 | .436 | .446 |
| | White | .776 | .746 | .720 | .694 | .676 | .685 | .705 | .589 | .698 |
| | Black | .816 | .796 | .781 | .758 | .750 | .766 | .785 | .688 | .770 |
| Samples | $X_1$, $X_2$, $X_4$ | 1209 | 400 | 237 | 167 | 115 | 76 | 54 | 41 | 35 |
| | $X_3$ | 1092 | 361 | 214 | 151 | 104 | 69 | 49 | 37 | 32 |

FIGURE 6


Eo vs. Class-A Pan
5-day Period (mm/day)
Eo (mm/day)
Evap. of Class-A Pan (mm/day)
0
1
2
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12

The values of Row 2 to Row 5 in Table 6 are the correlation coefficients between $E_a$ and $X_2$, $X_3$, or $X_4$. It is obvious that the correlation between $E_a$ and $X_2$ is much lower than that between $E_a$ and $X_3$, or $X_4$. It is not suitable to use the Bellani plate to estimate Ea. High correlation between $E_a$ and $X_3$ or $X_4$ is satisfactory. For example, for $E_a$ and $X_3$ in the 5-day period, the line of best fit is given in Eq.(2.8); Figure 7 shows the scattered points for Ea Vs $X_3$.

$$E_a = 0.692X_3 - 0.731 \qquad (2.8)$$

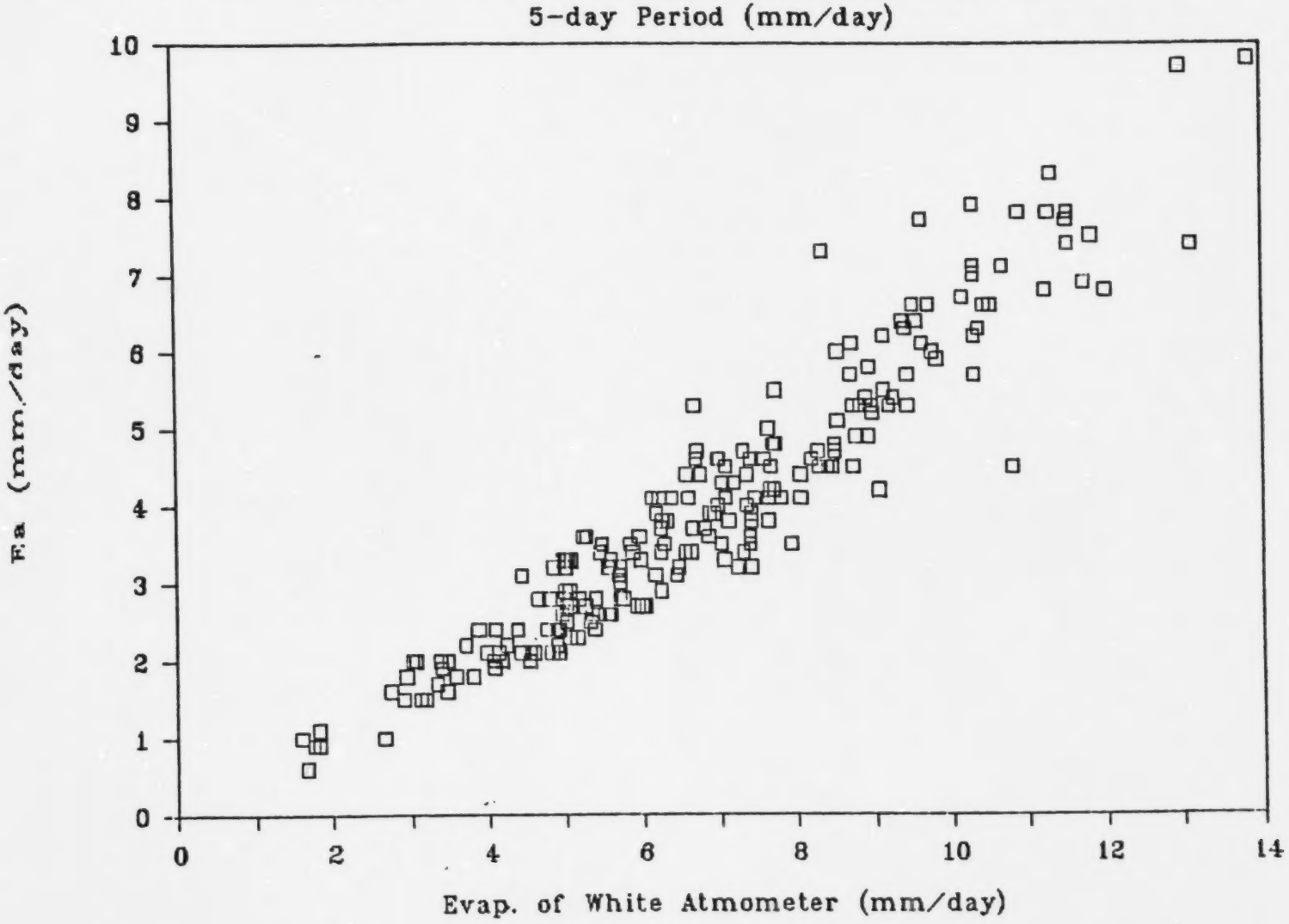
The mean standard error of the estimate is 0.506 which is 12 percent of $E_a$; the regression accounts for 90 percent of the variance. In comparison with the Class "A" pan, the white and black atmometers are more suitable for the estimate of the aerodynamic term of Penman's formula. It also suggests that white and black atmometers are more sensitive to the saturation vapour-pressure deficit and velocity of the air than is the Class "A" pan.

(b) Energy Balance Term ($E_e$)

The energy balance term of Penman's formula, $E_e$, is shown in Eq.(2.3). The correlation coefficients between $E_e$ and $X_1$, $X_2$, $X_3$, $X_4$ are listed in the middle of Table 6. Unlike the relationship discussed above, the correlation here is much lower than that between $E_a$ and $X_1$, $X_2$, $X_3$, $X_4$.

For the Class "A" pan, the correlation coefficient rises with the increase of time period during 15 days. It means that the response of the Class "A" pan has a time constant because of a mass of water. If

FIGURE 7 Ea vs. White Atmometer

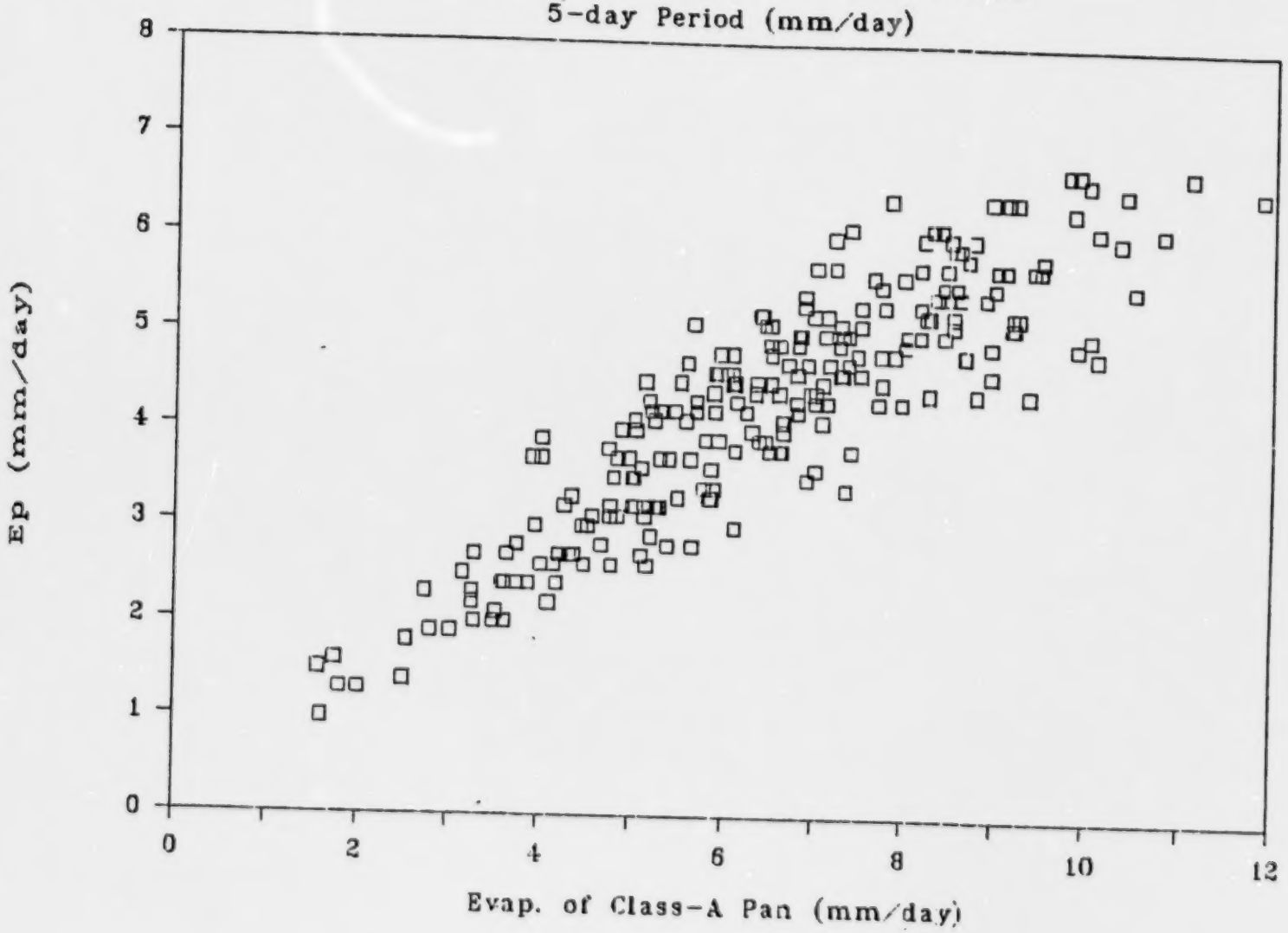


the average weather elements of a 15-day period are used (the highest correlation), the mean standard error of the estimate is 0.591 which is 20 percent of $E_e$; the regression accounts only for 53 percent of the variance. Even if a weighting factor of $E_e$, $\Delta/(\Delta+\gamma)$ is considered as in Eq.(2.5), the correlation coefficients have the range of 0.64 - 0.73. It does not make a big difference. So, the estimate of $E_e$ from the Class "A" pan is not as satisfactory as expected. For the other three atmometers, the correlation coefficients are as low as 0.5 or lower. Although the testing of the correlation coefficients reaches the level of significance, the error is too big to use $X_2$, $X_3$, or $X_4$ to estimate $E_e$.

(c) Potential Evapotranspiration ($E_p$)

As shown in Table 6, the correlation between $E_p$ and $X_1$ is better than that between $E_p$ and $X_2$, $X_3$, $X_4$. For more than a 3-day period the correlation coefficients are as large as 0.89. For instance, in the 5-day period the mean standard error of the estimate $E_p$ from $X_1$ is 0.564 which is 13 percent of $E_p$; the regression accounts for 79 percent of the variance. Figure 8 shows the scatter of the points Ep vs Class "A" pan. This estimate is much better than that from others. These results indicate that the pan is more responsive than the other three atmometers to the combination of radiation, humidity and wind, and thus, other things being equal, more suitable for evapotranspiration measurements. It is better to use the estimate over a 3-day period.

FIGURE 8 Ep vs. Class-A Pan



## 2.4 The Use of Evaporimeters in the Estimate of Evapotranspiration

Potential evapotranspiration is normally estimated from a solution of the energy-balance equation (the first term, $H\Delta/(\Delta+\gamma)$, in Eq.(2.5)) and the aerodynamic term equation (the second term, $E_a\gamma/(\Delta+\gamma)$ in Eq.(2.5)). Although the aerodynamic term in Penman's formula is usually half of the energy term, it shows great variation. Monteith (1961) has shown that there is little difference in the net radiation available to similar surfaces at different stations in the British Isles. If this result is of general application, it suggests that an estimate of evapotranspiration by Penman's formula may be obtained simply by using measurements or calculations of net radiation made at a weather station nearby and weighted according to the local air temperatures; adding to the energy term, the aerodynamic term is estimated from local measurements of the white (or black) atmometer.

For more simplification, the readings from the Class "A" pan and the white (or black) atmometer can be used jointly to generate daily values of Penman's $E_p$, especially in daily estimates.

As said above, among four evaporimeters, the measurements of the Class "A" pan are the best approximate values from which an empirical formula can be derived. In a rough estimate of $E_p$ over 3-day period, the empirical formula associated with Class "A" pan may have priority over others.

### (a) The Use of the White (or Black) Atmometer in Estimating $E_p$

As has been discussed before, the measurements of the white atmometer have a high correlation with $E_a$, the aerodynamic term of Penman's formula. In combined Eq.(2.5), the aerodynamic term has a

weighting factor $\gamma/(\Delta+\gamma)$. The correlation coefficients and the coefficients of the best fit line are listed in Table 7. It shows that a high correlation still exists between $E_a\gamma/(\Delta+\gamma)$ and $X_3$ (or $X_4$), especially for over a 3-day period. The mean standard error of the estimate is about 0.15 to 0.20 which is 11 - 15 percent of $E_a\gamma/(\Delta+\gamma)$; the regression accounts for about 80 - 83 percent of the variation. It indicates that the function of the White atmometer in estimating the weighted aerodynamic term is better than that of the Piche atmometer discussed by G. Stanhill (1961).

With the use of white atmometer to estimate $E_p$, Eq.(2.9) is obtained.

$$E_p = a' + b'[H\Delta/(\Delta+\gamma) + (a+bxc)] \qquad (2.9)$$

in which $H\Delta/(\Delta+\gamma)$ is weighted energy term; a+bxc is weighted aerodynamic term estimated from the White atmometer, a and b are shown in Table 7. Unlike G. Stanhill (1961), a+bxc is preferred in estimating weighted aerodynamic term rather than $C\gamma/(\Delta+\gamma)$, because the former estimate has a higher correlation and less standard error than the latter.

Table 8 shows the values of linear regression of Eq.(2.9). All correlation coefficients were over 0.98. The differences in the total annual evapotranspiration estimated by the two methods were less than 1 cm or 2 percent. The maximum differences found were 0.4 - 0.7 mm per day or 9 - 13 percent with respect to over 3-day period calculation. Figure 9 shows the line of the best fit between $E_p$ and combined estimate of Eq. (2.9).

Using Eq.(2.9) to estimate $E_p$, the weather parameters needed are air temperature, dew point, and global radiation or duration of sun-

Table 7. Regression Coefficients for $X_3$ (and D) $E_a\gamma/(\Delta+\gamma)$

| | $X_3$ (x) | $E_a\gamma/(\Delta+\gamma)$ (y) | | $X_4$ (x) | $E_a\gamma/(\Delta+\gamma)$ (y) | |
|---|---|---|---|---|---|---|
| | R | a | b | R | a | b |
| 1-day | 0.904 | 0.0159 | 0.1909 | 0.880 | -0.0808 | 0.1615 |
| 3-day | 0.908 | 0.0272 | 0.1921 | 0.886 | -0.0266 | 0.1619 |
| 5-day | 0.917 | 0.0799 | 0.1843 | 0.899 | -0.0268 | 0.1571 |
| 10-day | 0.915 | 0.0725 | 0.1863 | 0.900 | -0.0343 | 0.1586 |
| 20-day | 0.914 | 0.0916 | 0.1841 | 0.897 | -0.0111 | 0.1559 |

Table 8. Regression Coefficients for Eq.(2.9)

| | R | a' | b' | $\sigma_{yx}$ | $\sigma_{yx}/E_p$(%) |
|---|---|---|---|---|---|
| 1-day | 0.983 | 0.1179 | 0.9719 | 0.3029 | 7.2 |
| 3-day | 0.985 | 0.1391 | 0.9674 | 0.2327 | 5.5 |
| 5-day | 0.988 | 0.1267 | 0.9704 | 0.1893 | 4.4 |
| 10-day | 0.990 | 0.1424 | 0.9672 | 0.1556 | 3.6 |
| 20-day | 0.992 | 0.1315 | 0.9696 | 0.1284 | 2.9 |

shine. The aerodynamic term is estimated from the readings of white atmometer instead of using the measurements of wind.

(b) A Simplifying Estimate of $E_p$ for Daily Use

As discussed in the section 2.3, the white atmometer is suitable to estimate the aerodynamic term, and Class "A" pan is sensitive to the energy balance. Although a Class "A" pan can probably be used to estimate $E_p$ for over 3-day period, it still has a low correlation in daily use. This might be improved with the use of Class "A" pan and the white atmometer in an approximate operation. This operation needs only the readings of the Class "A" pan and the white atmometer without any measurement of weather elements.

Eq.(2.10) is the daily combined estimate of $E_p$ from Class "A" pan and the white atmometer:

$$E_p = a' + b' \ (a_1 + b_1 * X_1 + a_2 + b_2 * X) \qquad (2.10)$$

in which $a_1 + b_1 * X_1$ is the estimate of the energy term from Class "A" pan, and $a_2 + b_2 * X_3$ is the estimate of the aerodynamic term from the white atmometer. The correlation coefficient is 0.84 (0.82 for $E_p$ and $X_1$, seen in Table 6). The mean standard error of the estimate $E_p$ from $X_1$ and $X_3$ is 0.90, which is 21 percent of $E_p$; the regression accounts for 71 percent of the variance. It can be seen in Table 9 that the correlation coefficient rose to 0.85 and improved a little.

FIGURE 9

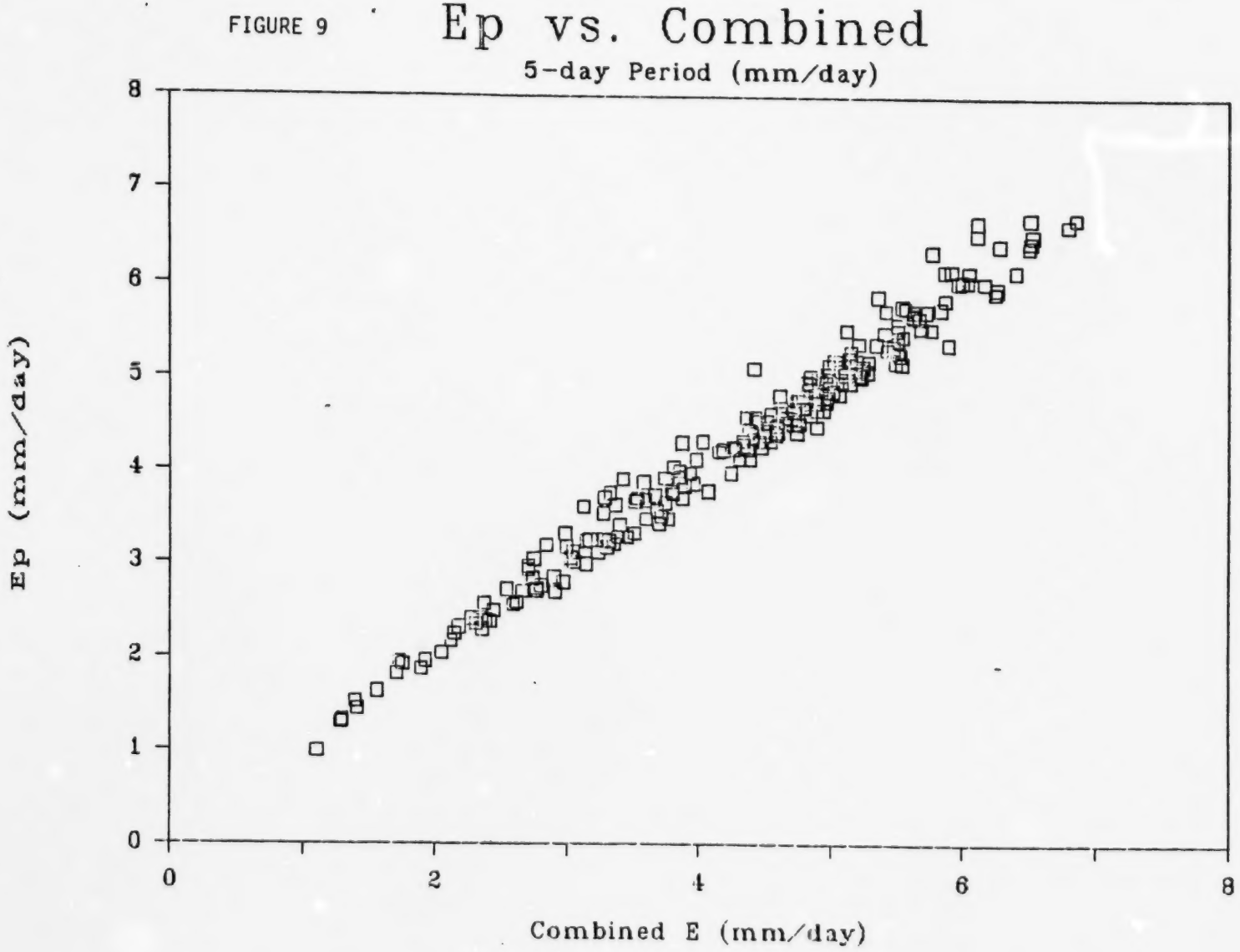

Ep vs. Combined
5-day Period (mm/day)
Ep (mm/day)
Combined E (mm/day)
0
1
2
3
4
5
6
7
8
0
2
4
6
8

Table 9. Coefficients of $E_p$ from $X_1$, and $X_3$ and $X_4$

| | R | a' | b' | $a_1$ | $b_1$ | $a_2$ | $b_2$ |
|---|---|---|---|---|---|---|---|
| $E_p$ $X_1+X_3$ | 0.84 | 0.076 | 0.98 | 1.13 | 0.27 | 0.016 | 0.19 |
| $E_p$ $X_1+X_4$ | 0.85 | -0.063 | 1.02 | 1.13 | 0.27 | -0.081 | 0.16 |

## 2.5 Conclusion

With 11 years of data observed at CRS of the SRC, evapotranspiration estimates from four evaporimeters were made. It showed that some estimates were encouraging, while some were not suitable for routine use.

(a) In estimating the aerodynamic term of Penman's formula. The correlation between $E_a$ and $X_3$, $X_4$ is higher than that between Eo and $X_1$. It is obvious that atmometers are sensitive to the wind and the saturation vapour deficit.

(b) In estimating the energy balance term of Penman's formula, four evaporimeters are not satisfactory. The Class "A" pan has a higher correlation than others. Three atmometers have failed in their estimations.

(c) In estimating evapotranspiration from the combined formula, especially for longer than a 3-day period, the Class "A" pan is the best instrument. The pan is more responsive than others to combinations of radiation, humidity and wind.

(d) Simplifying the estimation of $E_p$, it is acceptable to use the white atmometer to estimate the aerodynamic term in Eq.(2.9) instead of measuring wind mileage. And further, the data of solar radiation may be obtained from a weather station not far from the site; it is easy to measure mean daily air temperatures and dew points.

(e) The Class "A" pan can be used to estimate the approximate value of $E_p$ beyond a 3-day period. Without any weather elements, Eq.(2.10) might be the daily combined estimate of $E_p$ from Class "A" pan and the white atmometer.

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